V International FFAG Workshop
Kyoto University Reactor Research Institute
Osaka, Japan
December 5-9, 2005

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BNL January 13, 2006

Brief History of FFAG Accelerators

- Invented 50 years ago by K. Symon and T. Ohkawa
- 120-keV spiral-sector FFAG betatron

  400-keV radial-sector FFAG betatron

  electron prototypes built and operated at MURA late 50's early 60's
- Concept was abandoned because FFAG had complicated magnetic structure and much greater cost with respect to conventional AG machine of same energy.
- Revival about 15 yrs ago because of proposal to use FFAG as Spallation Neutron Sources. But then again soon dismissed.

Muon Acceleration

- About 15 yrs ago new concepts of Muon Colliders and Neutrino Factories.
- Need to accelerate Muons to 20 (50) GeV very fast because of their short lifetime.
- Several Accelerators were considered

    RCS too slow, excludes

    SCL (200 MHz) too cumbersome, expensive

    RCL a' la CEBAF, not possible to separate
    beams because of the too large betatron
    emittance of the muon beam
- FFAG seemed (and is) only possible solution
- A sequence of meetings then were initiated to study Acceleration of Muons in FFAG rings
- … But there were soon problems …

Proton Acceleration

- In the meantime two FFAG prototypes (POP) were built, commissioned and operated at KEK
- They were 50 and 150 MeV Proton Accelerators.
- Obviously the interest soon included possible acceleration of Protons in various applications.
- It is here and now that the C-A Department got eventually also involved.
- BNL is involved in two fronts:

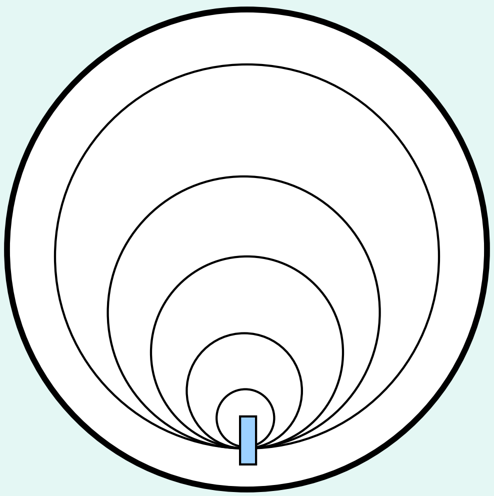
  Acceleration of Muons (Trbojevic, Palmer, Berg)

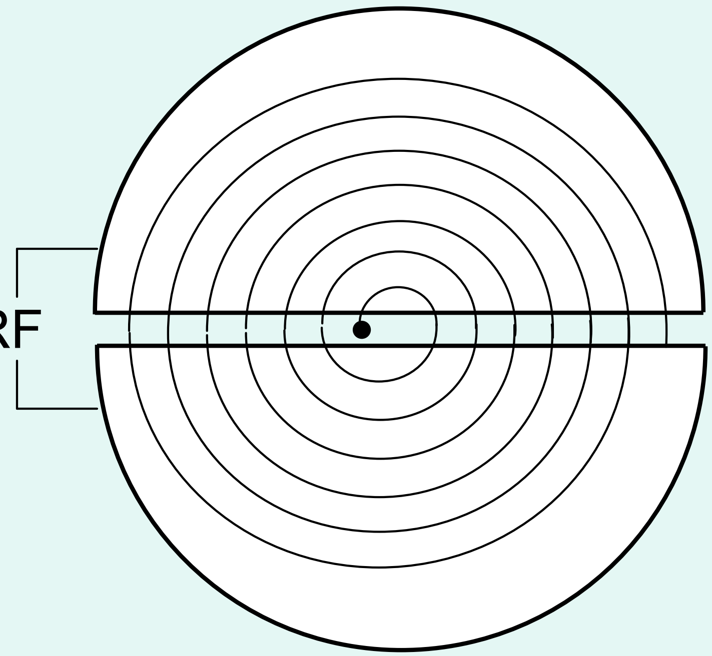
  Acceleration of Protons (Ruggiero, Trbojevic)
- I went to Osaka to report work on Proton FFAG.
- And so FFAG were back in business

Fixed-Field Accelerators

Cyclotrons and Microtrons are FF Accelerators.

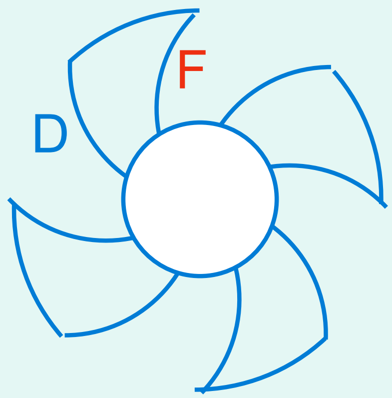
They are also Weak Focussing with Constant Field Profile. That is they are not AG



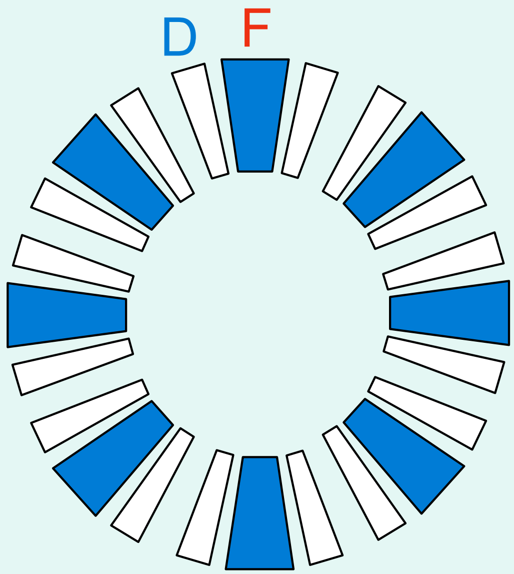


Fixed-Field Alternating-Gradient

- Spiral Sector FFAG
- Radial Sector FFAG



Edge Focusing



Reverse Bend

- FFAG Betatrons
- FFAG Synchrotrons
  - Acceleration in Phase (Protons)
  - Gutter Acceleration (Muons)

FFAG Lattice Choices

Scaling Lattice (KEK)

Alternating Field Profile chosen so that all trajectories have same optical parameters, independent of particle momentum (zero radial chromaticity) achieved with

$B = B_0 \; (r/r_0)^{-n}$

But very large Physical aperture to accommodate large momentum range (±30-50%). Large bending field. Limited insertions. Energy limitation. Expensive. It prefers DFD triplet.

Non-Scaling Lattice (Muon Collaboration)

Alternating Linear Field Profile. Large variation of optic parameters over required momentum range (Large Chromaticity). But compact Physical Aperture. Large Insertions. Lower magnetic fields. It prefers FDF triplets. Large energies possible. Expected to be cheaper.

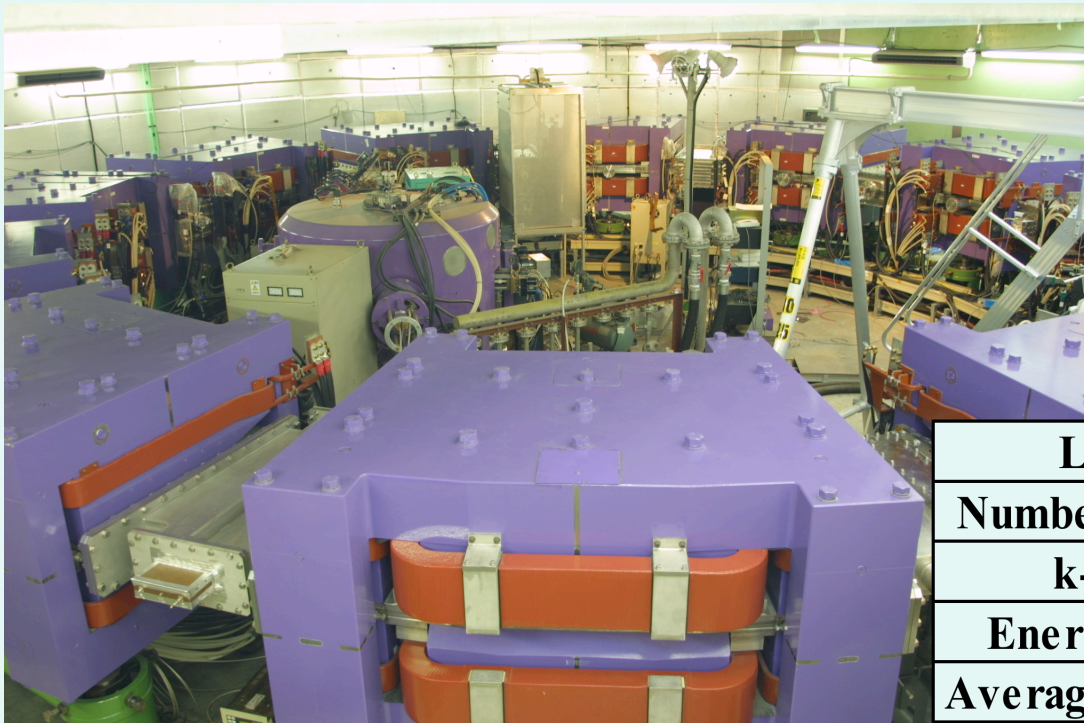
Status of KEK 150MeV FFAG

M. Aiba (KEK)
For KEK FFAG Gr.

Purpose of150MeV FFAG

- To be a prototype FFAG for various applications
  - Beam extraction from FFAG for the first time
  - Rapid cycling
  - Test experiments for applications using extracted beam

Machine parameters



Lattice	Triplet (DFD)
Number of sector	12
k-value	7.6
Energy (MeV)	12→150 (10→125)
Average radius(m)	4.47→5.20
Betatron tune	Hor.: 3.69∽3.80
	Ver.: 1.14∽1.30
Maximum field (T)	F: 1.63
(on orbit)	D: 0.78

Status of FFAG Complex at KURRI

M. Tanigaki, Y. Mori, K. Mishima, S. Shiroya, M. Inoue, RRI, Kyoto University
Y. Ishi, S. Fukumoto, Mitsubishi Electric Company
S. Machida, KEK

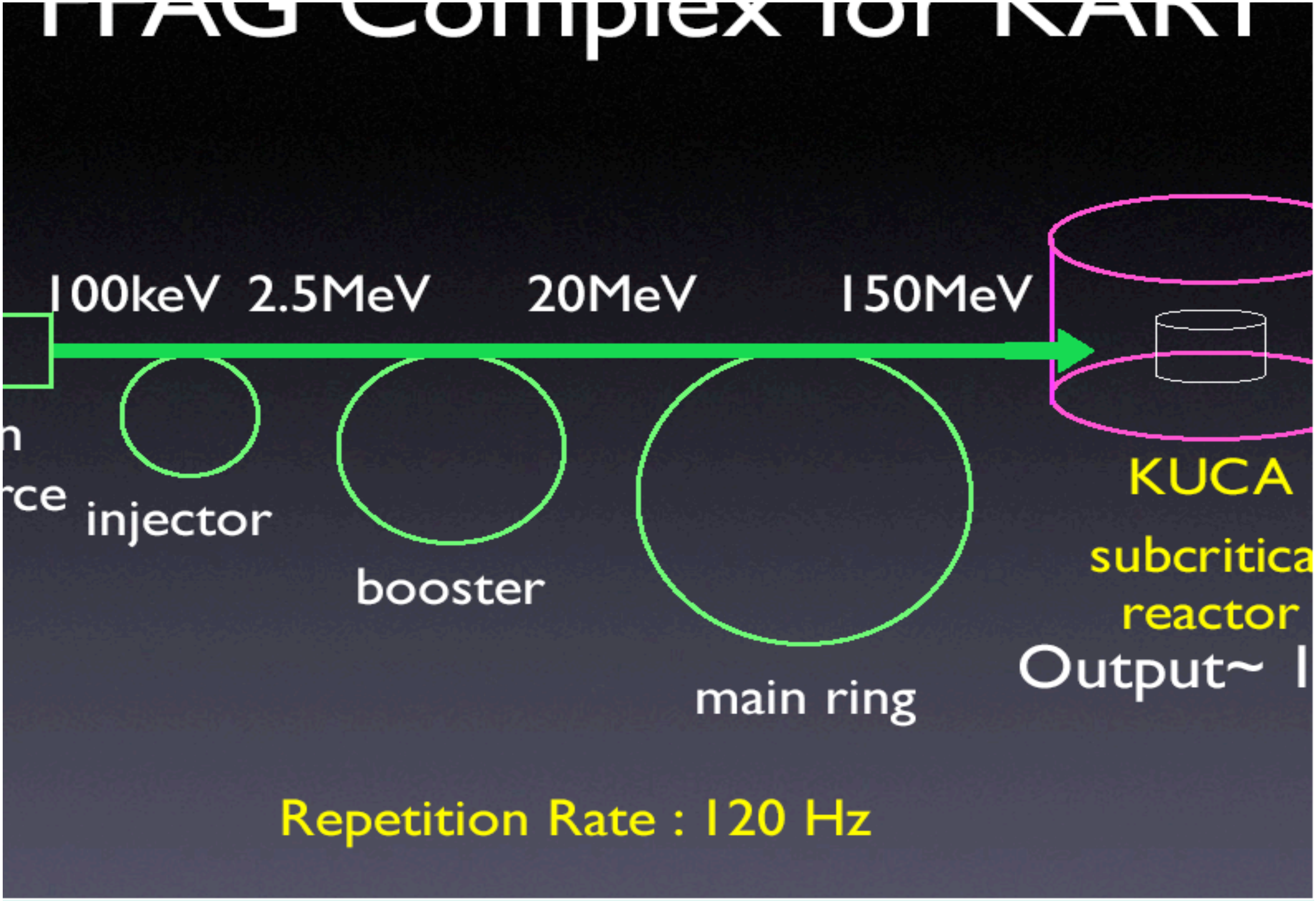
KART Project

Kumatori Accelerator driven Reactor Test

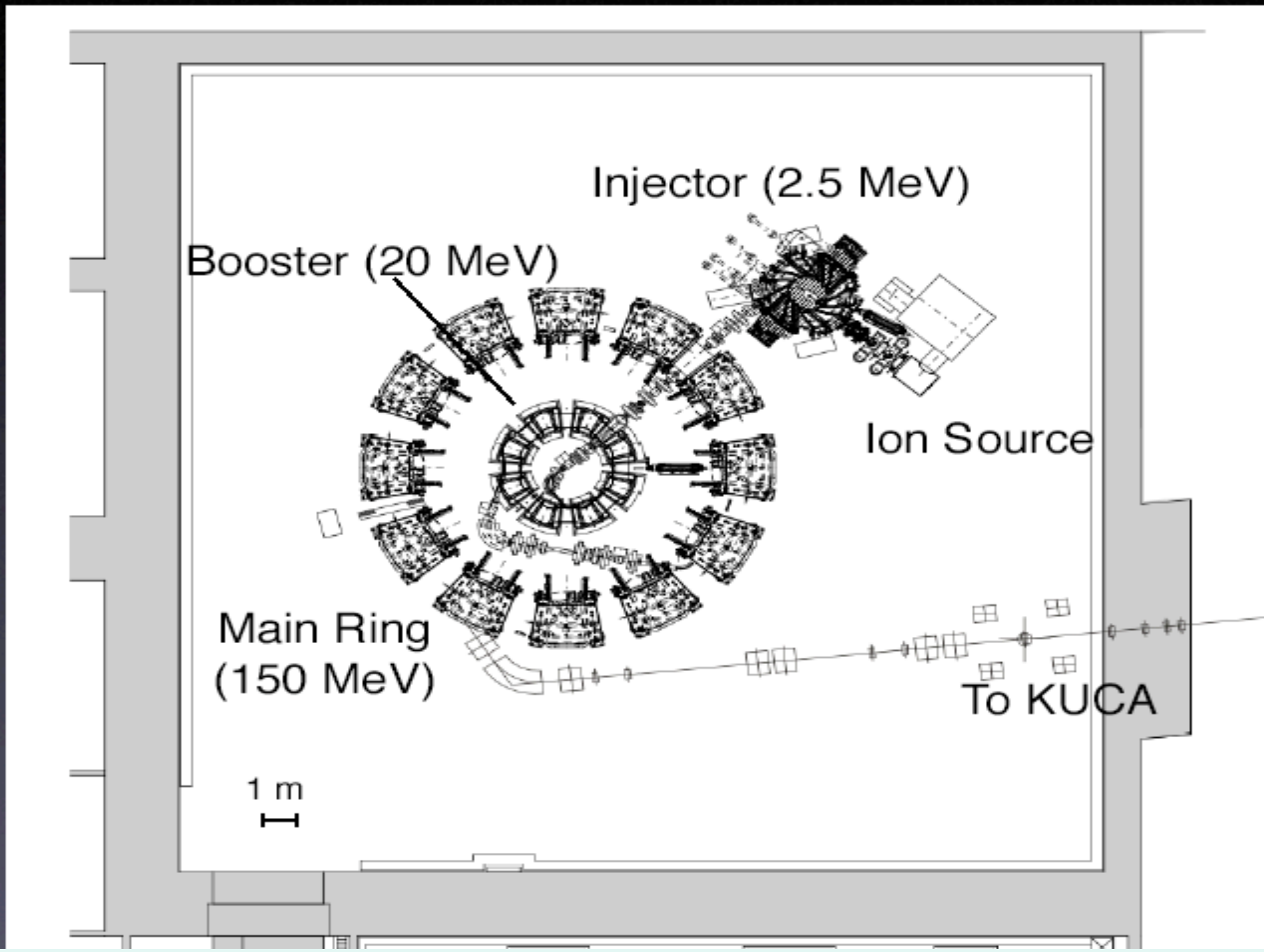
Purpose: Feasibility study of ADS

- k_{eff} for E_p = 20~150 MeV
- FFAG accelerator as proton driver for ADS

Five-year project (2002~2007)


100keV
2.5MeV
20MeV
150MeV
injector
booster
main ring
KUCA
subcritica
reactor
Output~ l
Repetition Rate : 120 Hz

FFAG complex

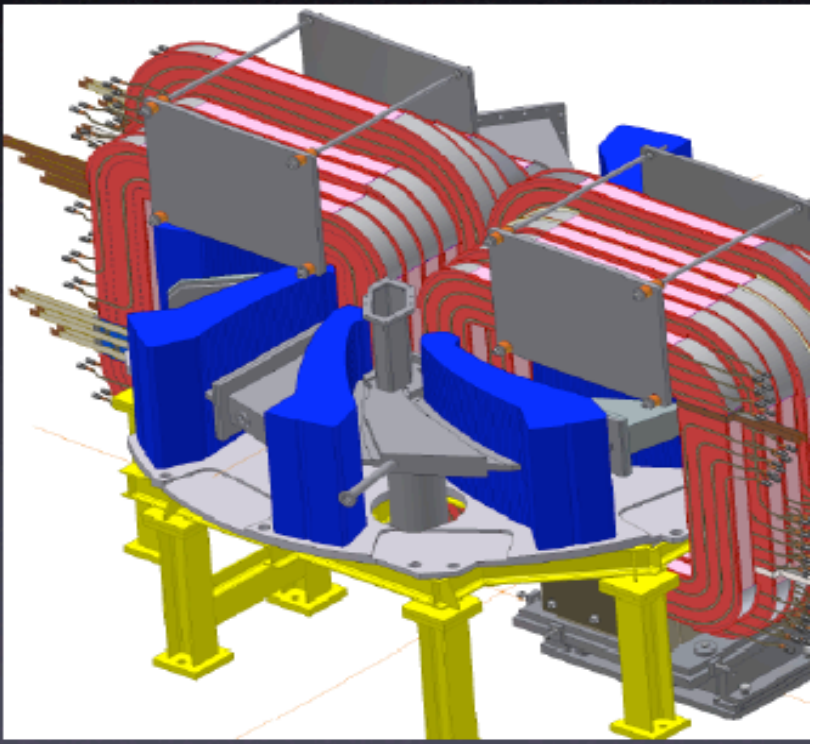


arameters for FFAG comple

	Injector	Booster	Main
E_{inj}	100 keV	2.5 MeV	20 MeV
E_{ext}	2.5 MeV	20 MeV	150 MeV
attice type	Spiral	Radial DFD	Radial DFD
# of cells	8	8	12
cc. scheme	Induction	RF	RF
k	2	2.45	7.5
coil/pole	coil	pole	pole
p_{inj}/p_{ext}	5.00	2.84	2.83
r_{inj}	0.60 m	1.27 m	4.54 m
r	0.88 m	1.74 m	5.12 m

Injector

rgy	0.4 ~ 2.5 MeV
>	0~2 μA
rate	0.1 ~1 kHz
ectors	8
angle	42 deg.
ze	3.5 m × 6 m × 2.5 m
ight	30 t



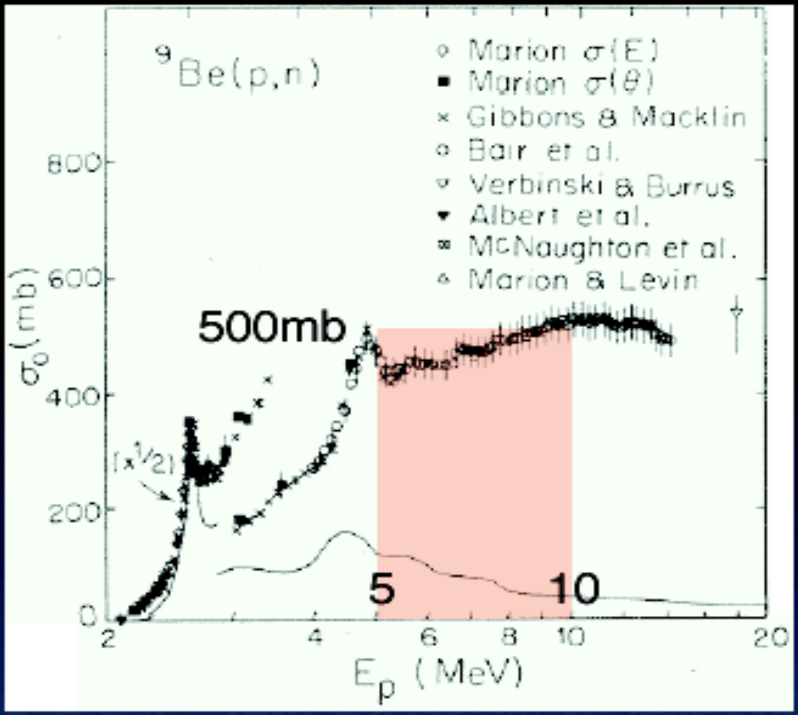
Neutron Source for BNCT
FFAG-ERIT scheme

Yoshiharu Mori
Kyoto University, RRI

Accelerator based Neutron Source

In order to obatin
φ>10E9 n/cm2/s

- Neutron production reactions
  - 9Be(p,n)B, 7Li(p,n)Be
- Proton beam
  - energy ~10MeV
  - current >20mA(cw)



Proton beam power is mostly consumed by ionization in the target, not by neutron production.

- Neutron production/Ionization(energy loss)

Efficiency ~ <1/1000

If the beam energy lost in the target is recovered by re-acceleration, the efficiency of neutron production can be improved.

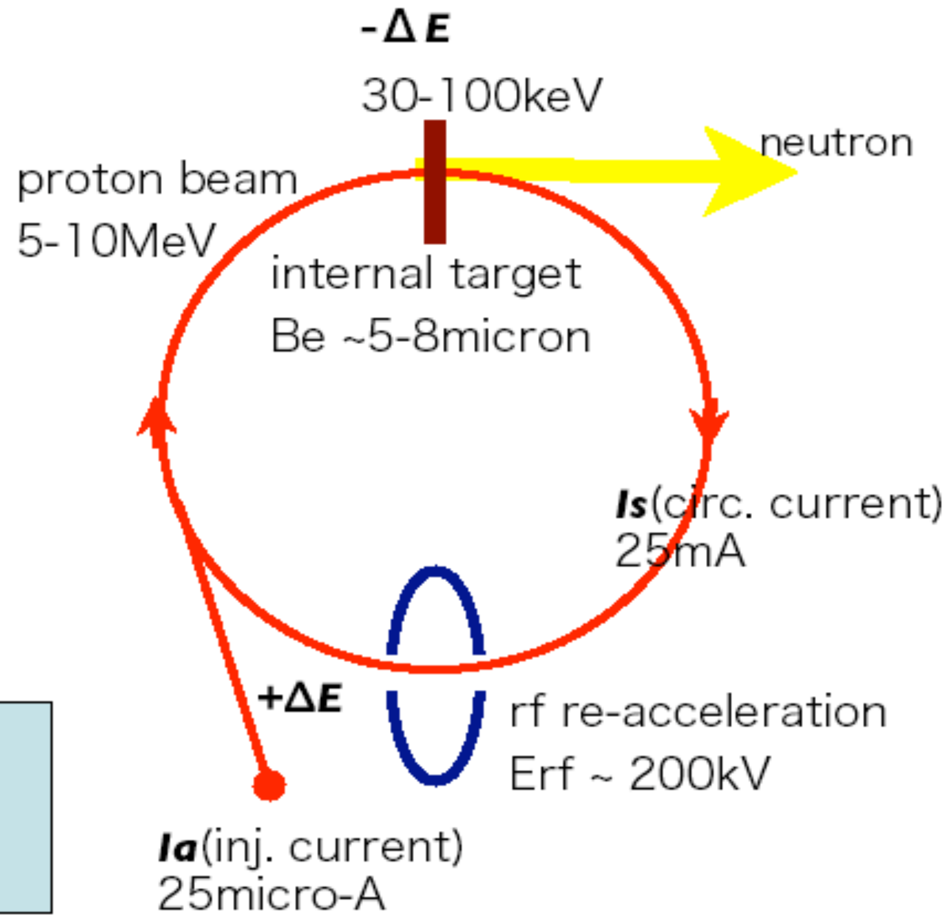
ERIT Energy Recovery Internal Target

for neutron production with FFAG accelerator

- Erergy loss
  - recovered by rf re-acceleration
- Emittance growth
  - cured by Ionization Cooling
- Beam current
  - reduced by storaging the beam in the ring

Ia=Is/Nt, Nt=1000turns

Need large momentum acceptance! -> FFAG



Emittance growth

- Using an internal target in the ring, the beam emittance can be increased in 3-D directions by Ratherford multiple scattering and stragling
- In ERIT scheme, however, the beam emittance growth can be cured by "Ionization Cooling" effect
- In other word, ERIT is "Ionization Cooling"

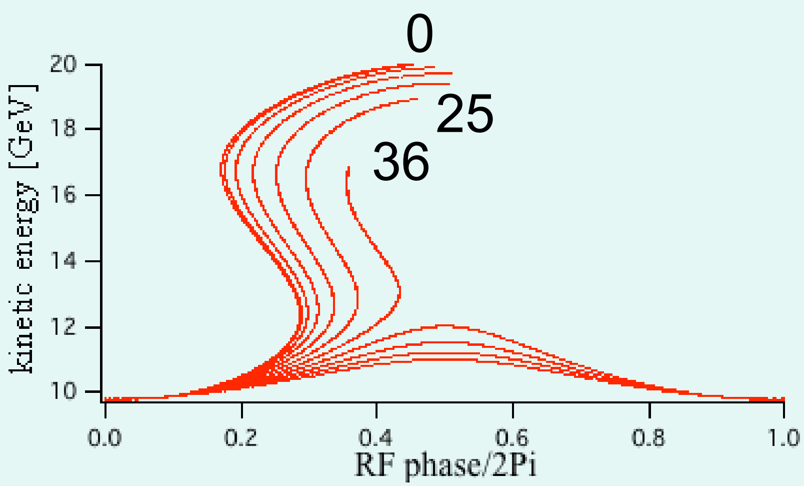
Muon FFAG

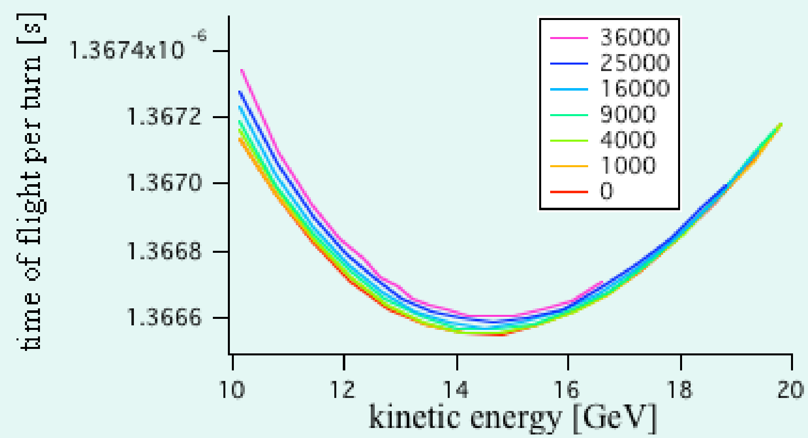
- Very little progress at the last Workshop
- Most of the discussion dealt with Proton FFAG
- An Energy of 20 (50) GeV is required for Neutrino Factory and Muon Collider.
- Presently Acceleration is proposed in three Rings
  - 2.5 - 5 GeV
  - 5 - 10 GeV
  - 10 - 20 GeV
- In each ring beam circulates at most 10 turns
- High SC RF (200 MHz) and Voltage System.
- Gutter Acceleration
- Isochronism Condition -> $\gamma = \gamma_T$
- Large Betatron Emittance ~ 30,000 π mm-mrad
- Study of FDF Non-Scaling Lattice (Trbojevic)

Acceleration with finite transverse emittance

S. Machida

- Horizontal amplitude are
  (0, 1, 4, 9, 16, 25, 36, 49, 64, 81, 100 x 10^3 p mm-mrad, normalized.)
- Vertical amplitude is zero.





- Difference of ToF becomes smaller as accelerated.

Summary

- Design of a Proton FFAG Accelerator
- Adjusted Field Profile
- CW Mode of Operation
- FFAG Accelerator for AGS Upgrade
- 1-GeV 10-MW FFAG Proton Driver
- FFAG Proton Driver for Neutrino Factory
- FFAG Medical Accelerator
- FFAG Electron Model (for Protons)

RF Acceleration -- CW Mode

In the pulsed mode of operation there is only a single beam being accelerated that occupies only one trajectory. In the CW mode of operation the beam is continuously accelerated and is present on every trajectory. The RF cavity system is tuned to a constant frequency and the beam is accelerated with a special voltage program designed to allow a programmable ***Harmonic Number Jump*** from one turn to the next.

Energy Gain per Turn $\Delta E = E_0 \beta^2 \gamma^3 / h \, (1 - \gamma^2 / \gamma_T^2)$

A.G. Ruggiero, "CW Mode of Operation of a Proton FFAG Accelerator", BNL Internal Report, C-A/AP 218, September 2005.

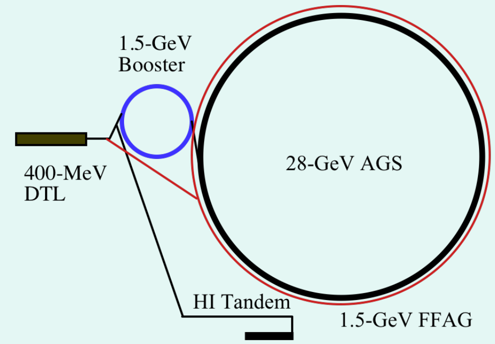
Isochronous Condition cannot be satisfied for Protons because $\gamma \ll \gamma_T$

Acceleration by RF has to be in the Bucket.

The advantage is that a single beam turn has a considerably lower intensity. If the turns are sufficiently differentiated from each other, the local space-charge effects will cause a more modest tune depression (~0.1) at much reduced beam emittance. Easier Beam Loading control.

RF can be very large frequency, higher voltage gradient, Superconducting, …

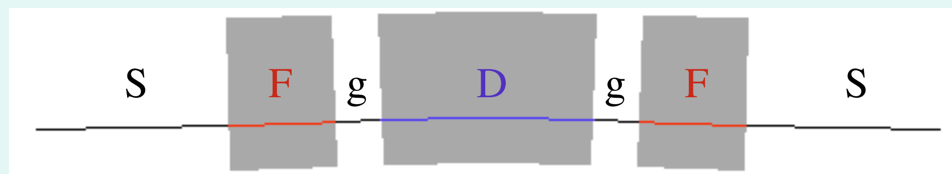
1.5-GeV AGS - FFAG

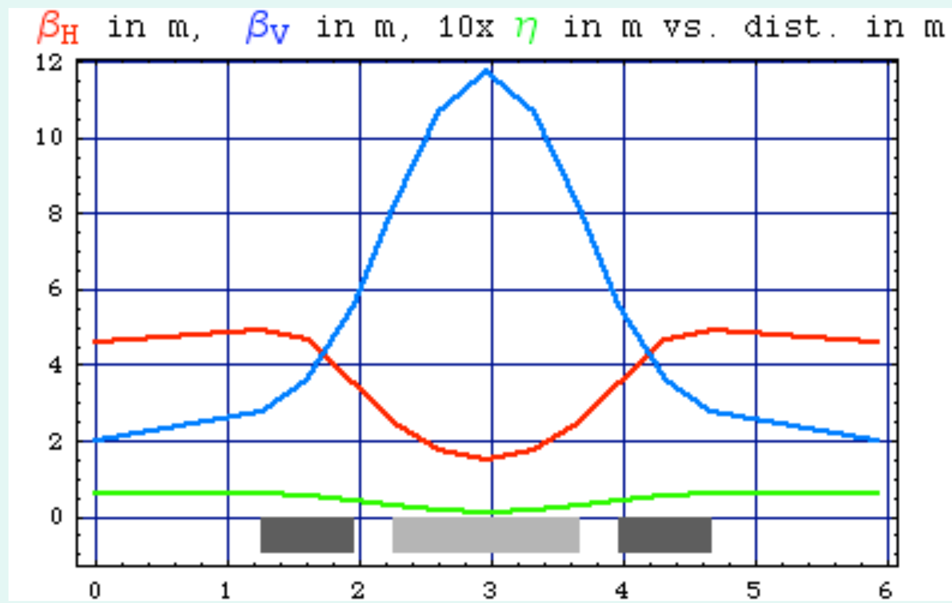


Energy Range		400 MeV - 1.5 GeV

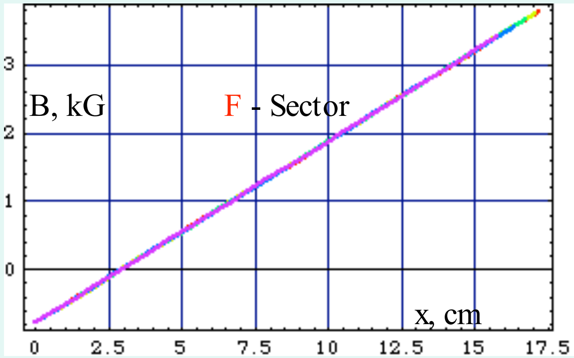
$p = \mathbf{p_0}\,(1 + \delta)$

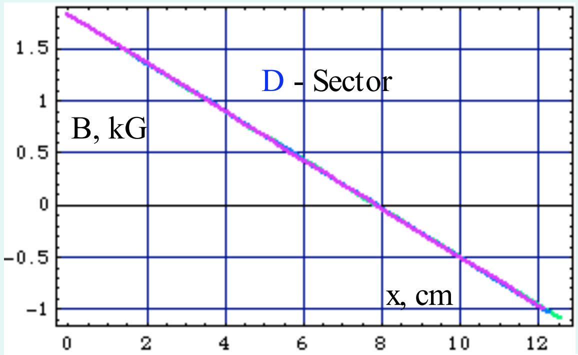
Reference Momentum, $\mathbf{p_0}$		954.263 MeV/c
Momentum Range, δ		0 - 1.36
Circumference		807.091 m
No. of Periods		**136**
Period Length		5.9345 m
Drifts:	Long (S)	2.5345 m
	Short (g)	0.3 m
F-sector:	Length	0.70 m
	Field	– 0.7841 kG
	Gradient	26.58 kG/m
D-sector:	Length	1.40 m
	Field	1.8345 kG
	Gradient	– 23.30 kG/m
Phase Advance / Period		105.23° / 99.93°
Betatron Tunes, ν_H / ν_V		39.755 / 37.755
Transition Energy, γ_T		105.482 i



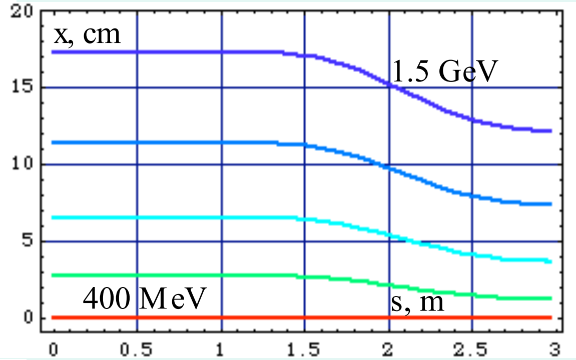


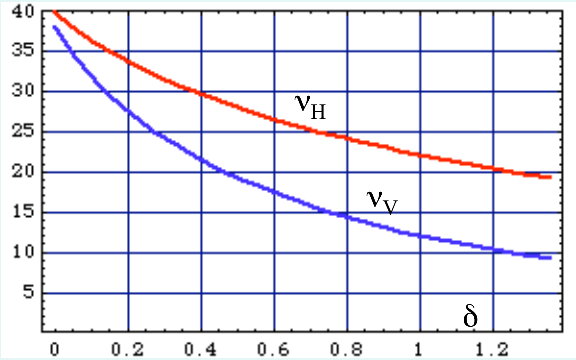
1.5-GeV AGS - FFAG

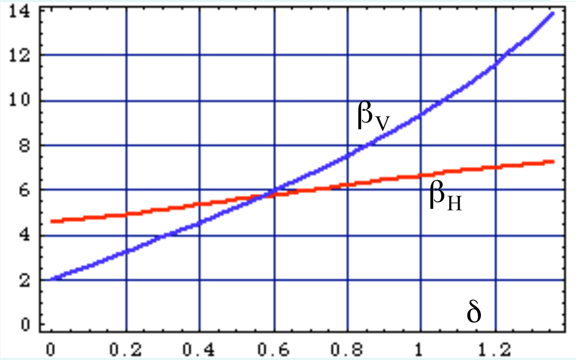




- A.G. Ruggiero, "1.5-GeV FFAG Proton Accelerator for the AGS Upgrade", Proceedings of EPAC-04, July 6-11, 2004, Lucerne, Switzerland
- A.G. Ruggiero, "Feasibility Study of a 1.5-GeV Proton FFAG in the AGS Tunnel",BNL Internal Report C-A/AP/157, June 20004

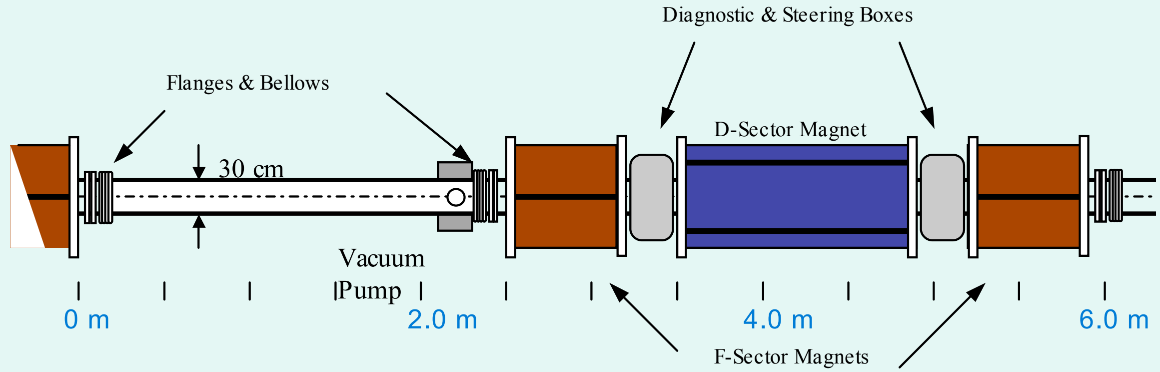






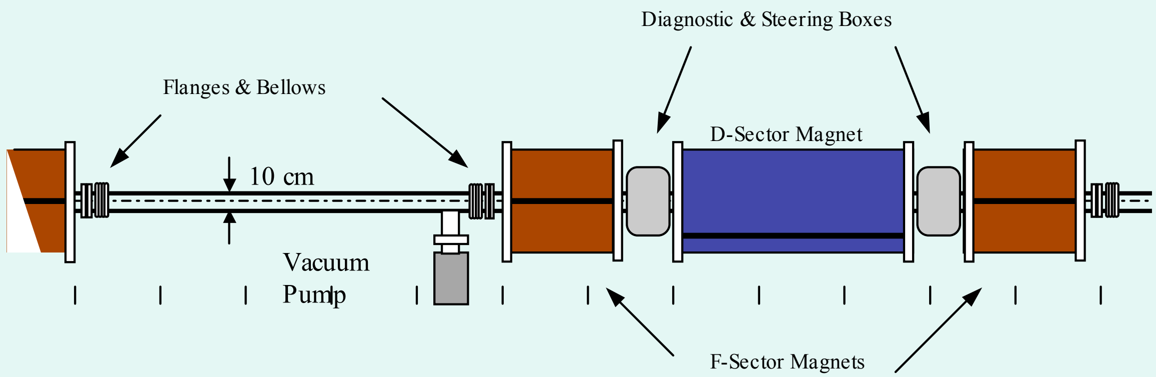
1.5-GeV AGS - FFAG

Top View



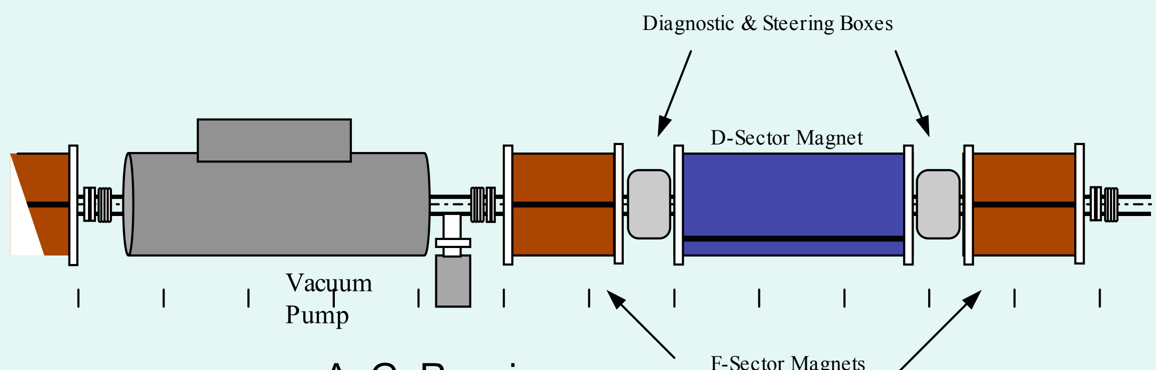
100 k$

Side View

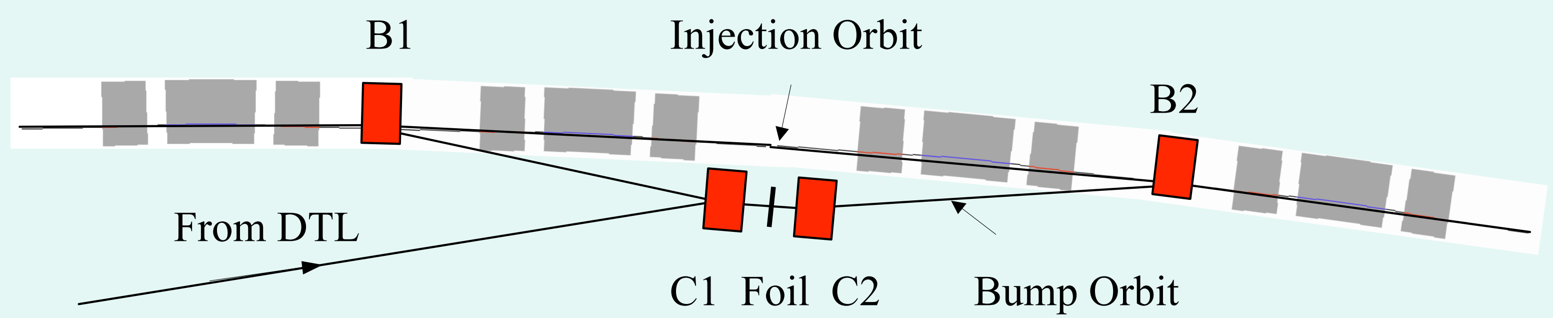


500 k$

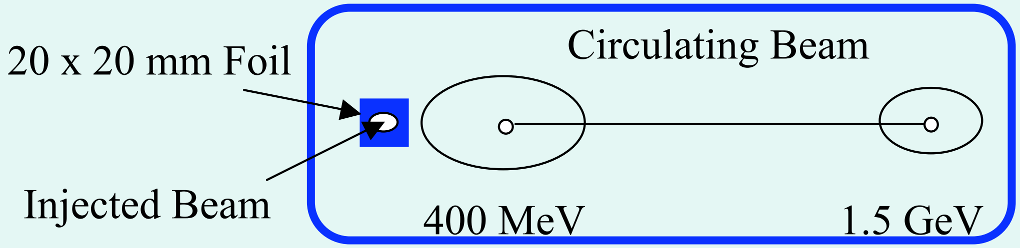
RF Cavity

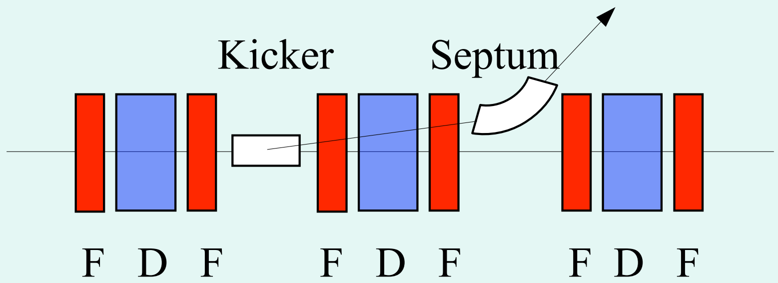


1.5-GeV AGS - FFAG



30 cm x 10 cm Vacuum Chamber

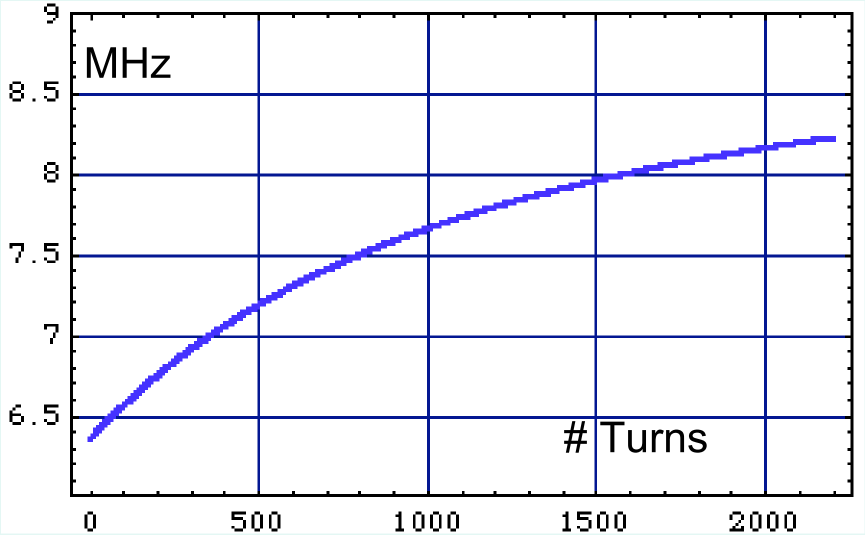




1.5-GeV AGS - FFAG

Circumference	807.091 m
Harmonic Number, h	24
Energy Gain	0.5 MeV / turn
Transition Energy, γ_T	105.5 i
Peak RF Voltage	0.8 MVolt
Number of full Buckets	22 out of 24
Total No. of Protons	1.0×10^{14}
Protons / Bunch	4.6×10^{12}
Injection Period	1.0 ms
Acceleration Period	7.0 ms
Total Cycle Period	8.0 ms

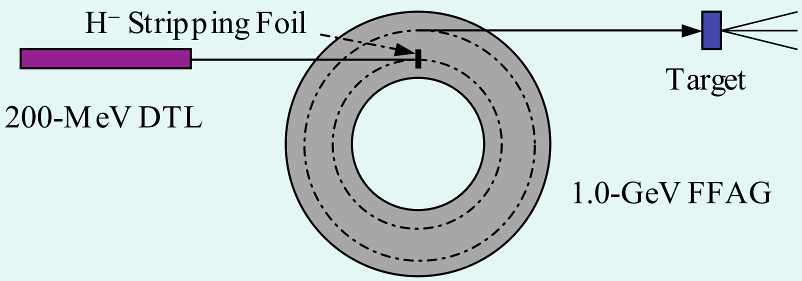
Linac Peak Current	35 mA
Chopping Ratio	0.50
Chopping Frequency	6.357 MHz
Single Pulse Length	0.96 ms
No. of Turns Injected	255
Repet. Rate	2.5 Hz
Linac Duty Cycle	0.24 %
Linac Beam Emittance, rms norm.	1 π mm-mrad
Final Beam Emittance, full norm.	100 π mm-mrad
Bunching Factor	3
SC Tune-Shift	0.50



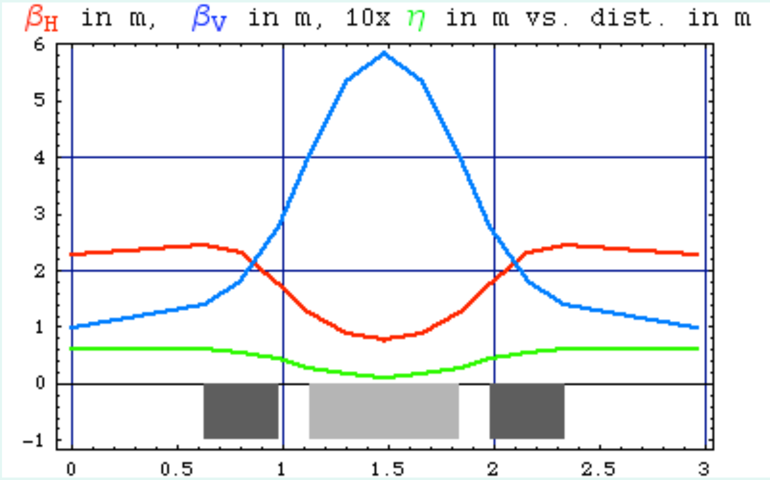
No. of RF Cavities	20	
No. of Gaps per Cavity	1	
Cavity Length	1.0 m	
Internal Diameter	10 cm	
Peak Voltage / Cavity	40 kVolt	
Power Amplifier / Cavity	250 kW	
Energy Range, MeV	**400**	**1,500**
β	0.7131	0.9230
Revol. Frequency, MHz	0.2649	0.3428
Revolution Period, μs	3.78	2.92
RF Frequency, MHz	6.357	8.228
Peak Beam Current, Amp	4.24	5.49
Peak Beam Power, MW	2.12	2.75

Generic Proton Driver

Injection Energy, U_i	200 MeV
Extraction Energy, U_f	1.0 GeV
Beam Ave. Power, $P = I\,U_f$	10.0 MWatt
Repetition Rate, F	1.0 kHz
Repet. Period, $\tau = 1 / F$	1.0 ms
Beam Ave. Current, $I = Ne\,F$	10.0 mA
Total No. Protons, N	6.25×10^{13}



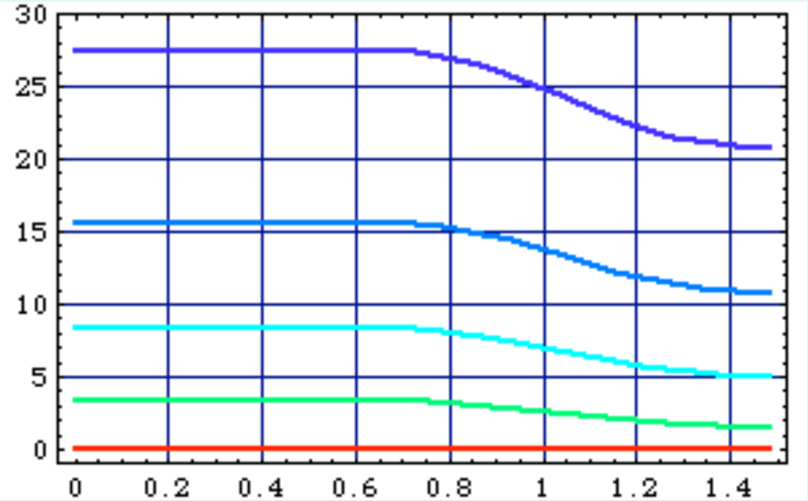
Circumference	201.773 m
Number of Periods	68
Period Length	2.96725 m
Short Drift, g	0.15 m
Long Drift, S (total)	1.26725 m
β_H max (in S)	2.27 m
β_V max (in D)	5.854 m
η max (in S)	0.0603 m
Phase Adv. / Period, H/V	105.10° / 99.802°
Betatron Tunes, H/V	19.8515 / 18.8514
Natural Chromaticity, H/V	–0.915 / –1.787
Transition Energy, γ_T	53.755 i

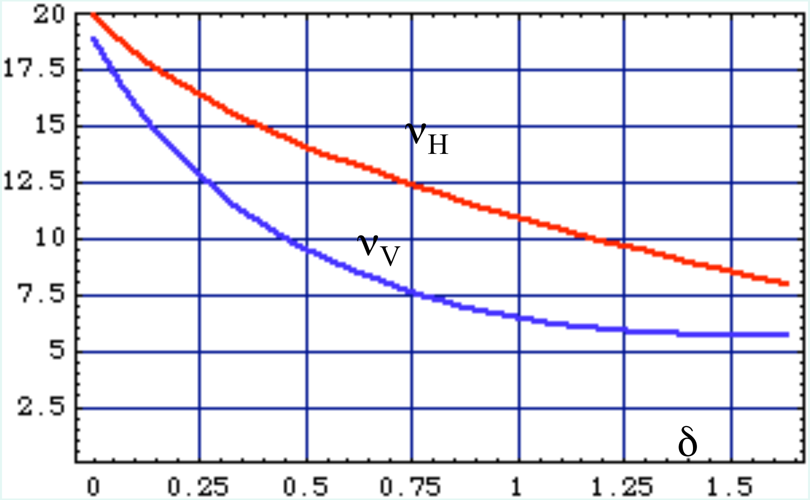


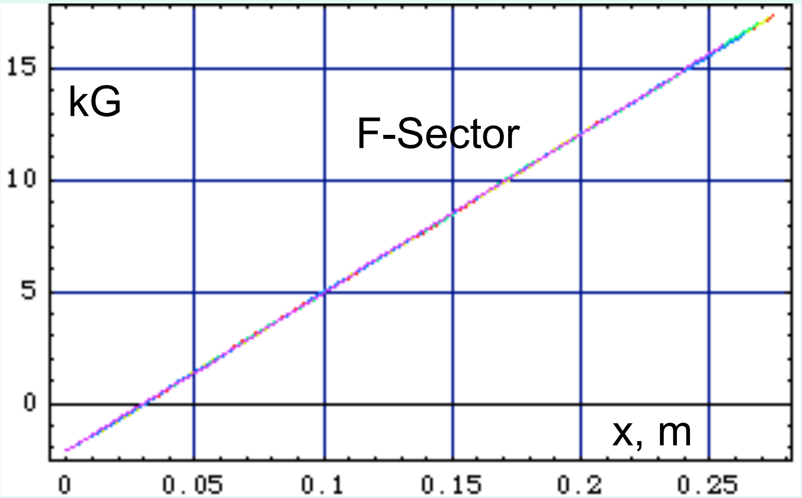
Magnet Type	F	D
Arc Length, m	0.35	0.70
Bending Field B, kG	– 2.118	4.956
Gradient G, kG/m	71.12	–23.30
Bending Radius ρ, m	–40.60	62.65
Bending Angle, mrad	–34.49	80.69

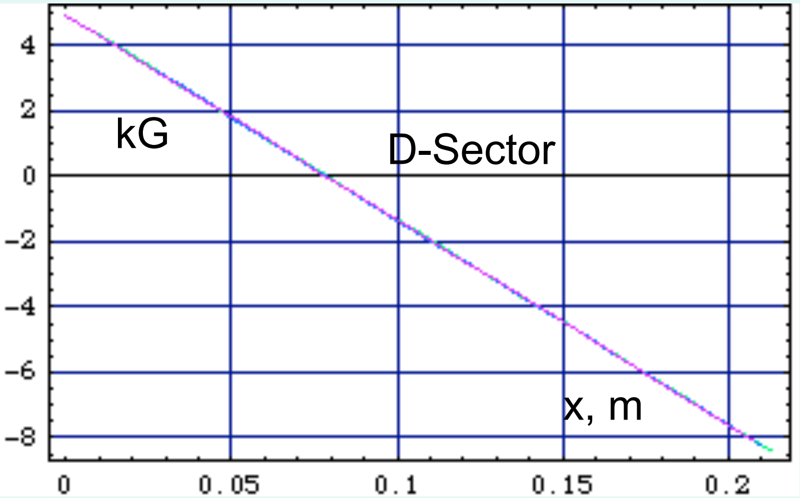
A.G. Ruggiero, “FFAG-Based High-Intensity Proton Drivers, Proceedings of the ICFA-HB2004 Workshop, Bensheim, Germany, Oct. 18-22, 2004

Generic Proton Driver



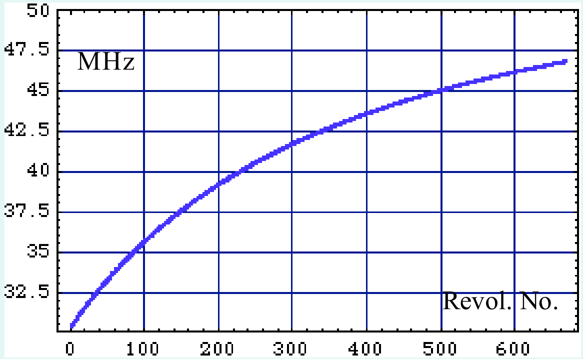






Generic Proton Driver

FFAG Circumference	C	= 201.8 m
	β_{ave}	= 0.75
Energy Gain	W	= 1.35 MeV / Turn
RF Peak Voltage	V_{RF}	= 1.8 Mvolt
Harmonic Number	h	= 36
No. Empty Buckets	9 out of 36	
Protons / Bunch	2.4×10^{12}	
No. of RF Cavities	40	
No. of Gaps / Cavity	1	
Cavity Length	1 m	
Peak RF Voltage / Gap	45 kVolt	
Power Amplifier / Cavity	0.8 MWatt	
Cavity Inter. Diameter	10 cm	
T-injection	0.333 ms	
T-acceleration	0.667 ms	



RF Modulation, Harmonic Number h = 36.

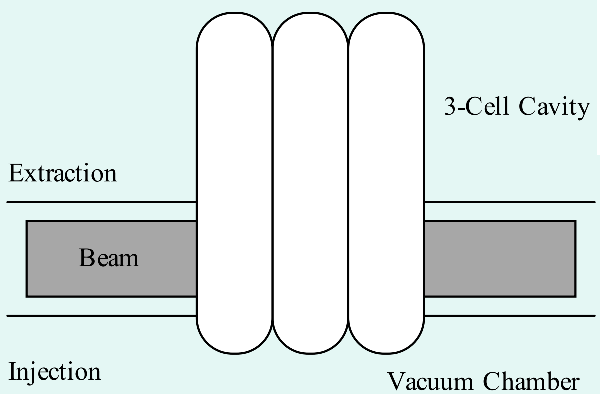
Issue # 1

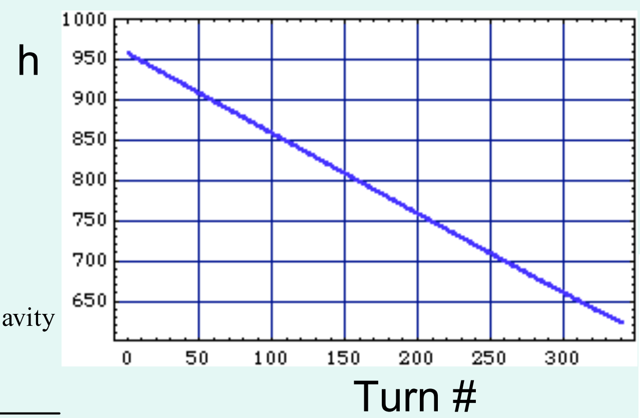
Can the RF ferrite be swept in 2/3 ms ?

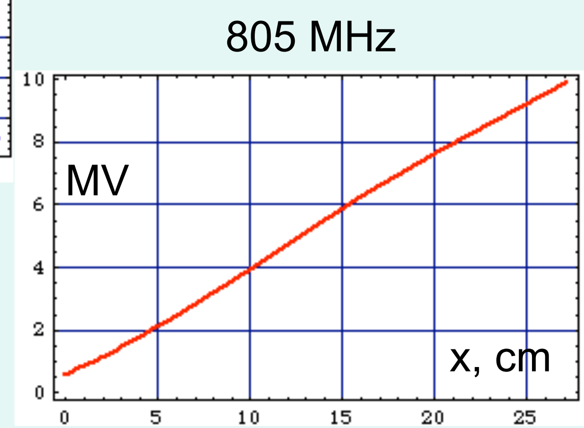
Energy Range, MeV	**200**	**1,000**
β	0.566	0.875
Rev. Frequency, MHz	0.841	1.300
Revolution Period, μs	1.189	0.769
RF Frequency, MHz	30.28	46.80
Peak Current, Amp	12.65	19.55
Peak Beam Power, MW	15.2	23.5

Generic Proton Driver

The design of a cavity cell that reproduces the longitudinal field profile may be problematic but not impossible. In the pill-box approximation, denoting with R the major transverse radius of the cavity, the longitudinal electric field varies with radius r according to the Bessel function J_0 (2.405 r / R) where r = 0 corresponds to the axis of the cavity. With the translation of coordinates $r = R - x_p$ it is seen that the Bessel function J_0 approximates the voltage curve at least in the ascending part. The beam is injected at x_p = 0 cm where the required field is minimum, and accelerated toward x_p = 27 cm where top energy is reached and the beam extracted. The cavity diameter is thus at least twice as large as the beam radial extension during acceleration (27 cm). A reasonable choice is R = 35 cm. The maximum value of the axial field is at x_p = 35 cm which corresponds to the r = 0 axis of the cavity. The cavity is thus transversally offset by a corresponding amount. The maximum value of the field is outside the beam range and approaches a value of 12 MVolt.

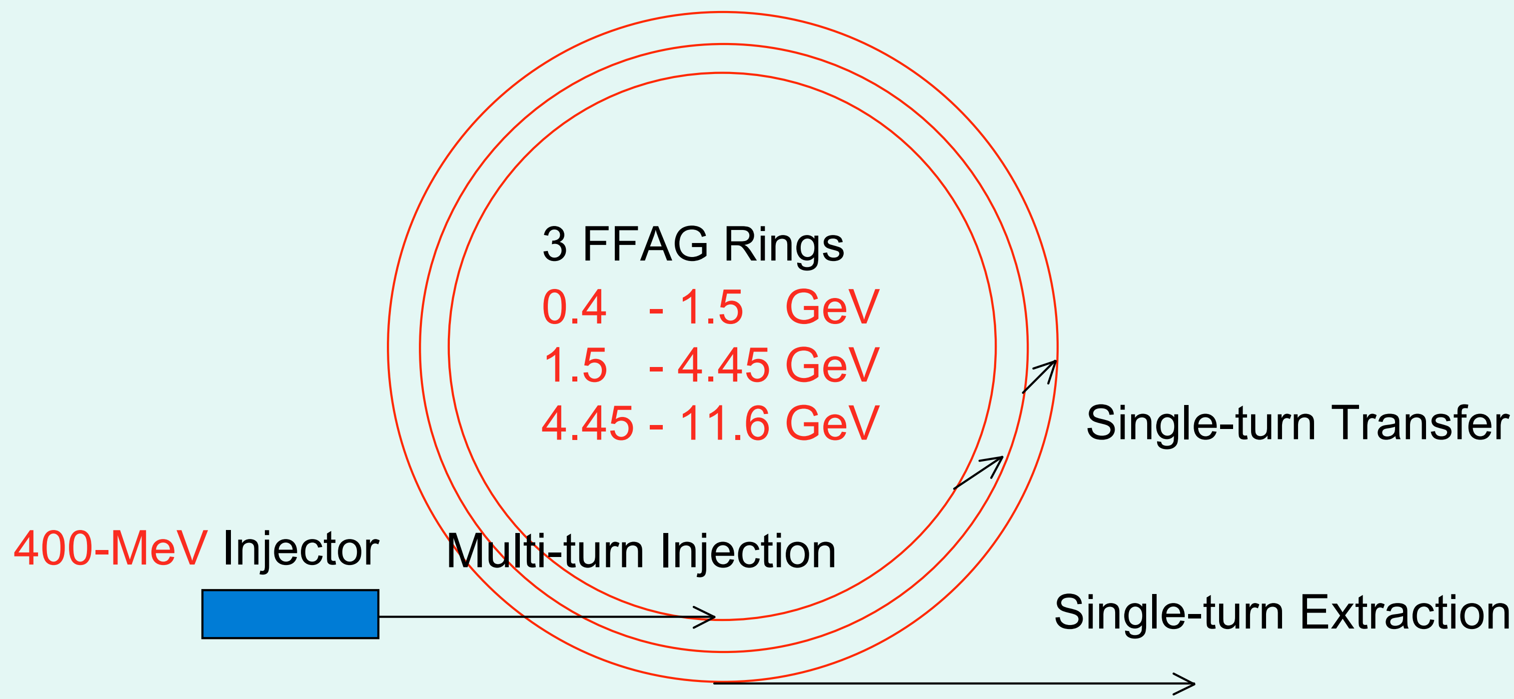






Proton Driver for Neutrino Factory

- A.G. Ruggiero,"FFAG Accelerator Proton Driver for Neutrino Factory", BNL Internal Report C-A/AP/219, October 2005, also Proceedings of NuFact05 Workshop, Frascati, Italy, June 2005



Muon vs. Proton FFAG Comparison

- Though at the present both studies assume FDF Triplets and Non-Scaling Lattice, there are major differences in Beam Dynamics and Engineering
- Space-Charge are important at Injection for Protons
- Large Emittance for Muons 30,000 vs 100 π mm-mrad
- β ~ 1 for Muons. β varies for Protons
- Superconducting Magnets for Muons
- Superconducting RF for Muons (constant frequency)
- RF modulation for Protons (Ferrite? How fast it can be swept?)
- Large RF Beam Loading for Protons
- $\gamma = \gamma_T$ for Muons vs. $\gamma << \gamma_T$ for Protons

Electron Model

- In both applications, the adoption of a Non-Scaling Lattice raises the serious concern of multiple crossing of major resonances.
- Though muons circulates only 10 turns and protons only 100 to 1000 turns, what is the effect on beam size and stability when crossing a resonance?
- Theoretical and Simulation work in progress
- Need of an Electron Model

    For Muons --> EMMA

    For protons --> SBIR

Electron Model for Proton FFAG Accelerator

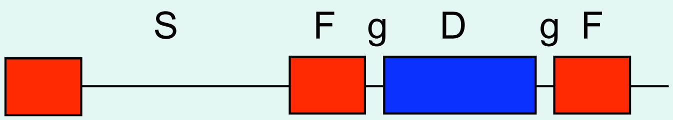


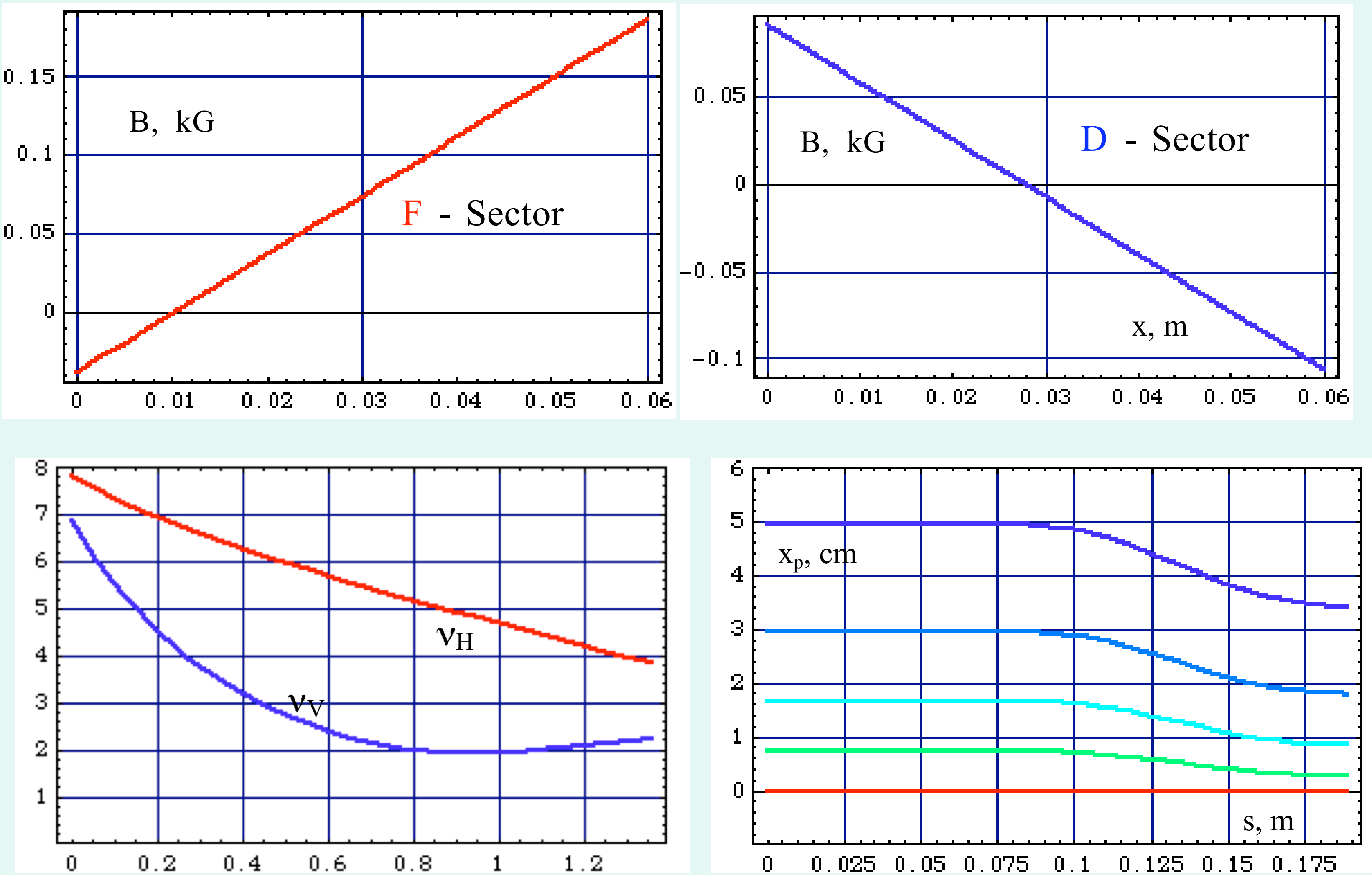
Table1. Lattice Parameters of Electron Model

Circumference	9.05484 m
Period Length	0.377286 m
No. of Periods	24
F: Length	4.375 cm
Field	–38.717 G
Gradient	3,739 G/m
D: Length	8.75 cm
Field	90.586 G
Gradient	–3,275 G/m
Drifts: S (half), cm	8.239
g (full), cm	1.875
Phase Advance, H/V	0.32589 / 0.28593
Betatron Tune, H/V	7.82122 / 6.86230
Transition Energy, γ_T	16.914 i
Chromaticity, H/V	–0.8274 / –1.8493

Table 2. Acceleration Parameters of Electron Model

	Injection	*Extraction*
Kinetic Energy, keV	217.85	816.93
Momentum, keV/c	519.73	1,225.66
β	0.71306	0.92300
Revol. Freq., MHz	2.3618	3.0552
Revol. Period, µs	0.4234	0.3273
Harmonic Number		3
RF Frequency, MHz	7.085	9.166
Bunch Area (full), eV-s		0.40
Peak RF Voltage, kVolt		5.824
Energy Gain, keV/turn		2.427
No. of Cavities		1
No. Electrons / Cycle		5.446×10^{10}
Circul. Current, mA	20.59	26.659
Beam RF Power, W	50.04	65.13
Space-Charge $\Delta\nu$	0.50	0.16
Full Emittance, norm.	100 π mm-mrad	
Repetition Rate, Hz	2.5	
Injection Period	0.1122 ms (255 turns)	
Acceleration Period	0.7854 ms (2,200 turns)	
Total Period	0.8976 ms	

Electron Model for Proton FFAG Accelerator



Next FFAG Workshop

- Semi-Annual International FFAG2006 Workshop
- BNL – May 15 - 19, 2006
- Danfords Inn and Marina
- Workshop Web Page available at the end of January
- Sponsored by DOE, BSA and BNL
- Contact People:
  - A.G. Ruggiero
  - Dejan Trbojevic
  - Anna Petway
  - Nick Franco